Modeling and Simulation within Computational Aerosciences

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Role of Computational Aerosciences

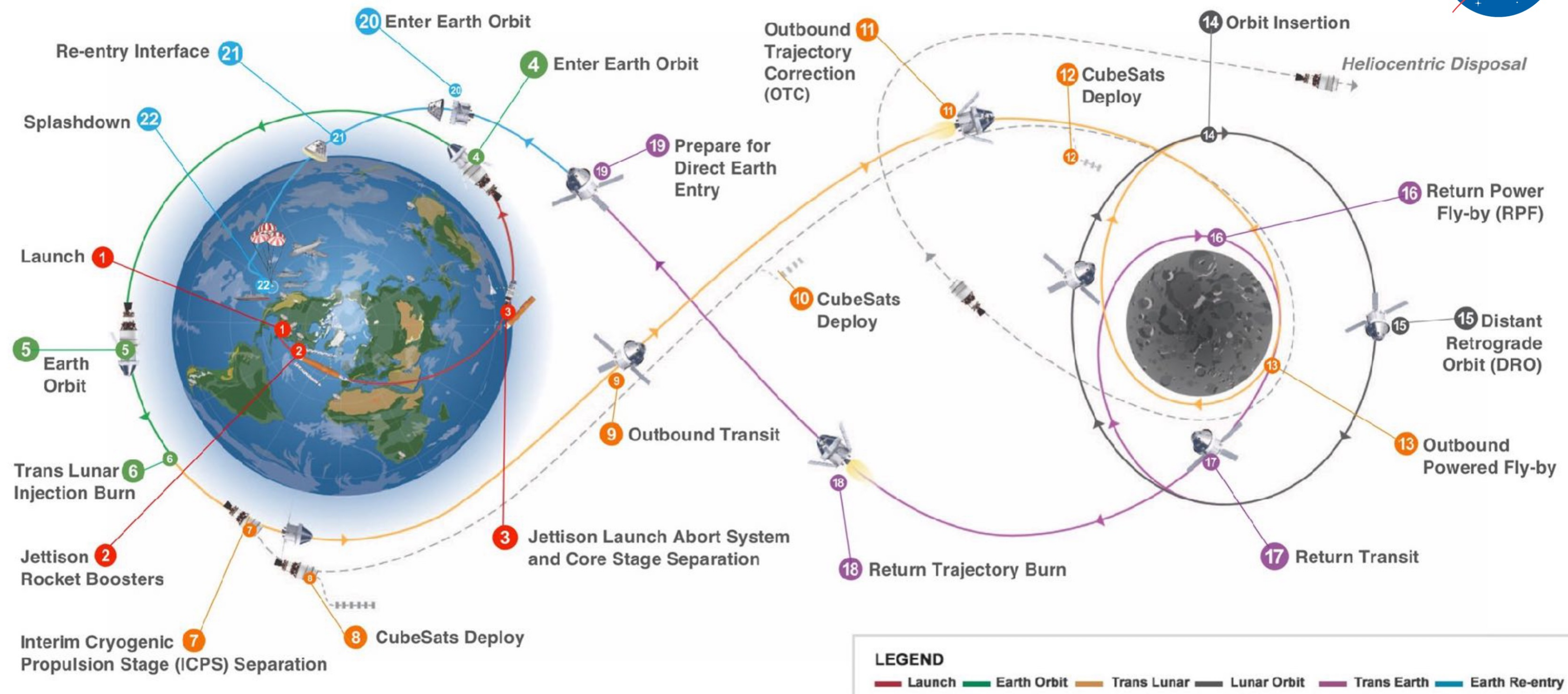
✓ **Perform large-scale simulations for**

- Human Launch : (SLS, MPCV, Commercial Crew) - Databases and induced environments for ascent and abort, staging, debris, plume impingement, retro-propulsion, launch environment
- Sustained Atmospheric Flight : aerodynamic/aeroacoustic/aerostructural performance prediction, vehicle design, noise prediction, airframe/propulsion integration, safety analysis

✓ **Advance computational aerosciences predictive capabilities to support NASA's current and future missions/needs/requirements**

- Aerodynamic
- Aeroacoustics
- Aerostructures

SLS Exploration Mission 1



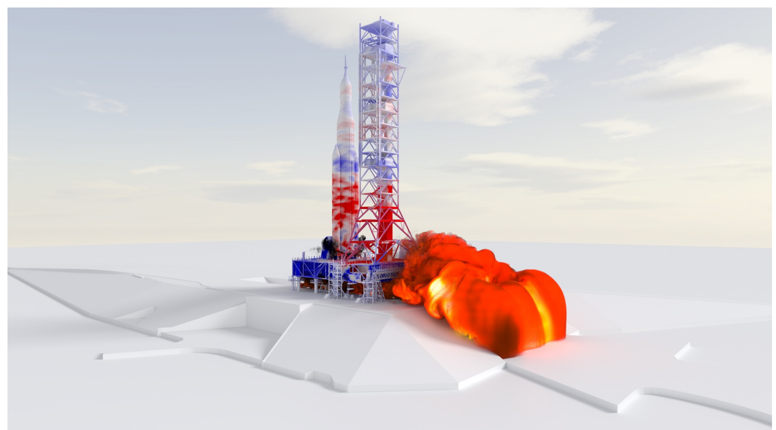
Total distance traveled: 1.3 million miles – Mission duration: 25.5 days – Re-entry speed: 24,500 mph (Mach 32) – 13 CubeSats deployed

Multiphysics Prediction Capability for Launch Environment

Photographs of a test of the KSC water deluge system which is used to suppress the immense sound pressure levels felt by the vehicle and surrounding structures during ignition.

- ✓ Goal of this project was to develop a capability for high-fidelity full-scale time accurate simulations of the launch environment acoustics including the water-based sound suppression system.

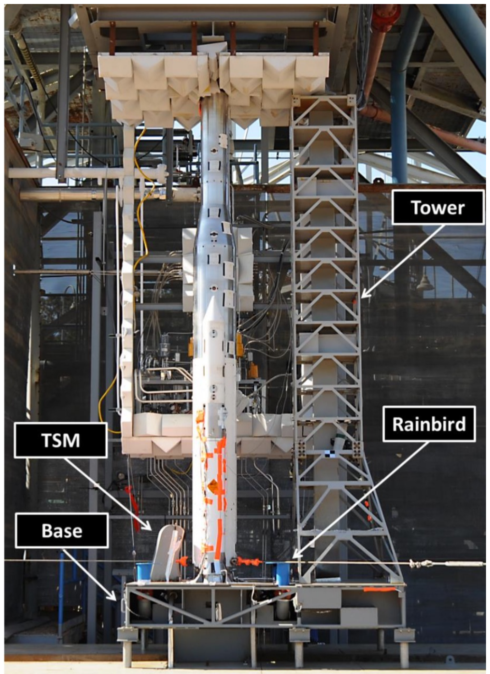
- ✓ Novel and provably stable high-order method for multiphase flow developed and integrated into the LAVA Cartesian AMR framework.



Visualization of previous LAVA SLS launch environment simulation without water deluge system. Particles track the plume path and are colored by temperature (white hot, dark cool). Surfaces are colored by pressure (red high, blue low).

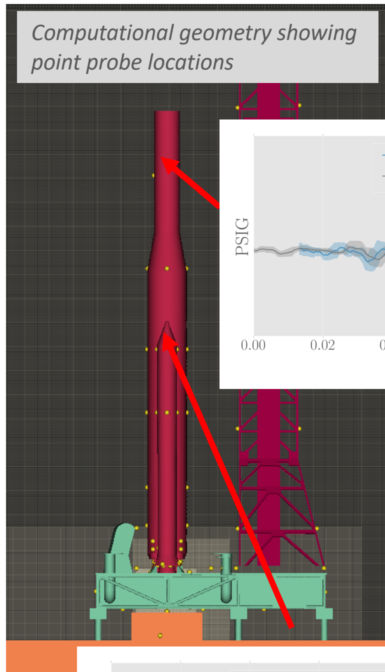
Validation with the 5% Scale Model Acoustic Test (SMAT)

multiphase simulations with plume & water

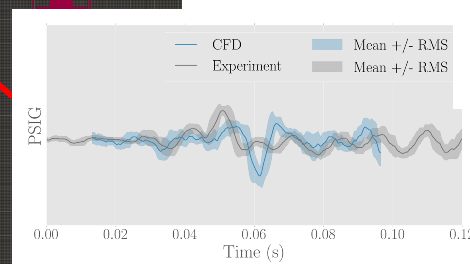


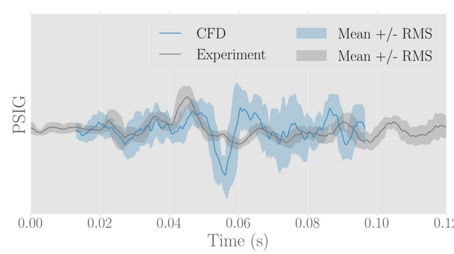
Photograph of the Scale Model Acoustic Test (SMAT)

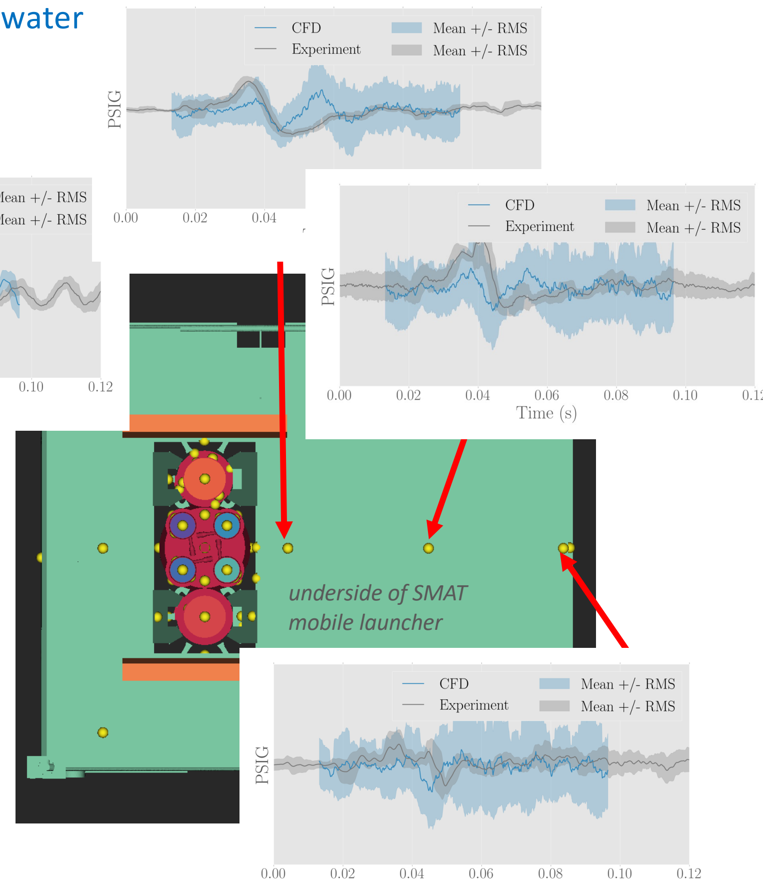
"Ignition Overpressure Computational Fluid Dynamics Simulation of Scale Model Acoustic Test PC123-FA-HF-01" Peter A. Liever February 2017



Computational geometry showing point probe locations



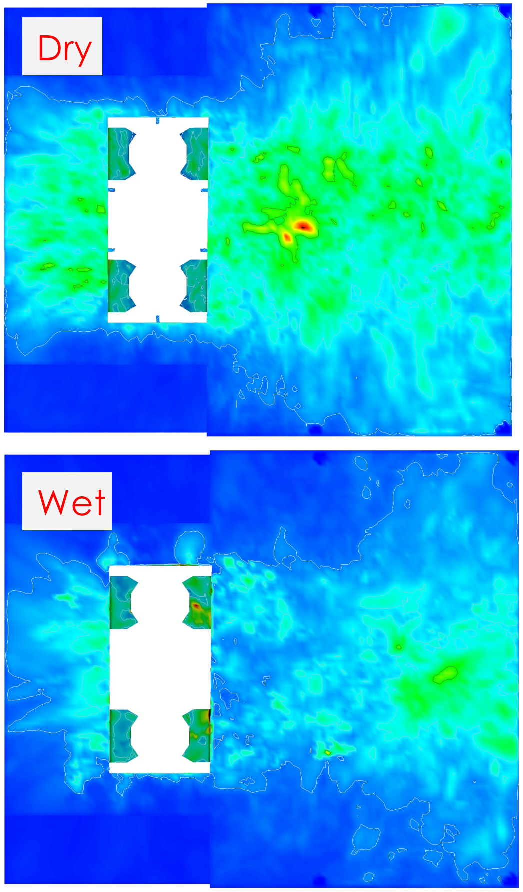




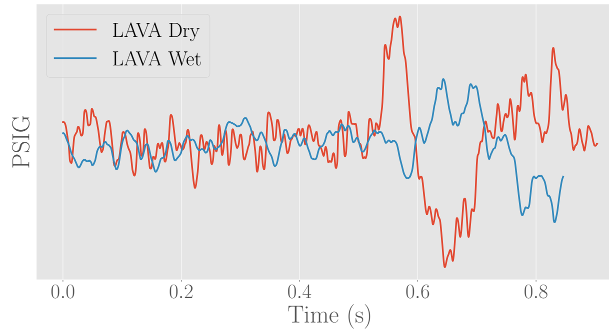
Comparisons of numerical (blue) pressure signal and recorded (gray) pressure signal as a moving average and with the shaded region showing RMS.

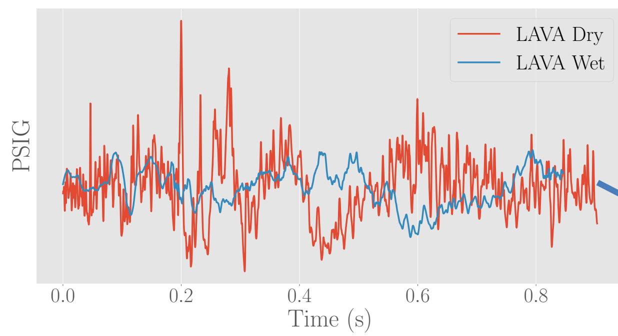
LAVA Simulations for Upcoming Artemis Flight at LC-39B

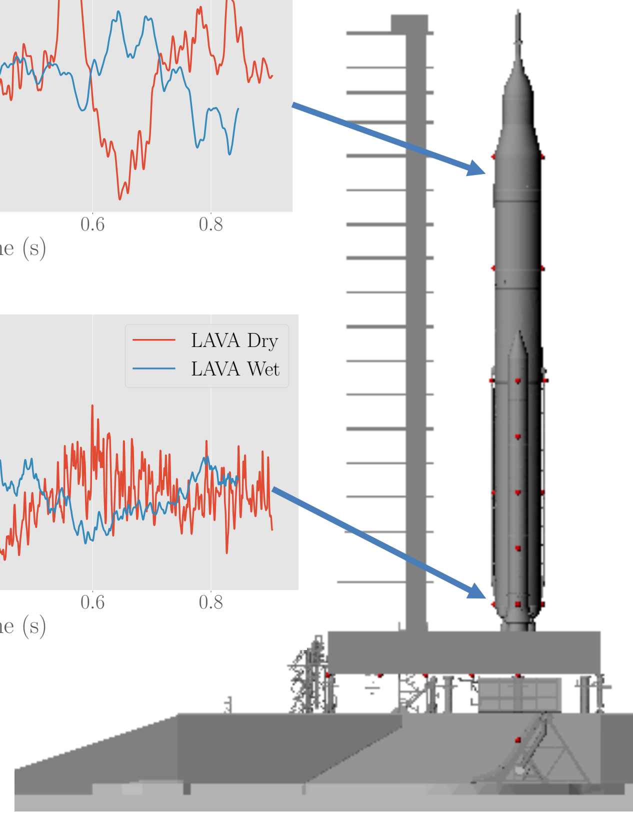
Maximum gauge pressure felt on the underside of Mobile Launcher during the ignition of the SLS engines.



Comparison of ignition overpressure wave for dry and wet case at two sensor locations on the vehicle.

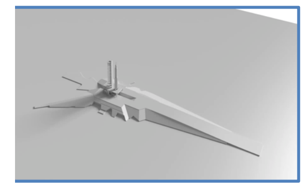


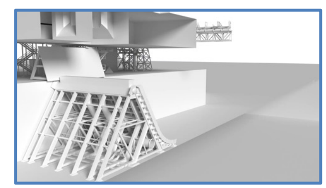




Movies:

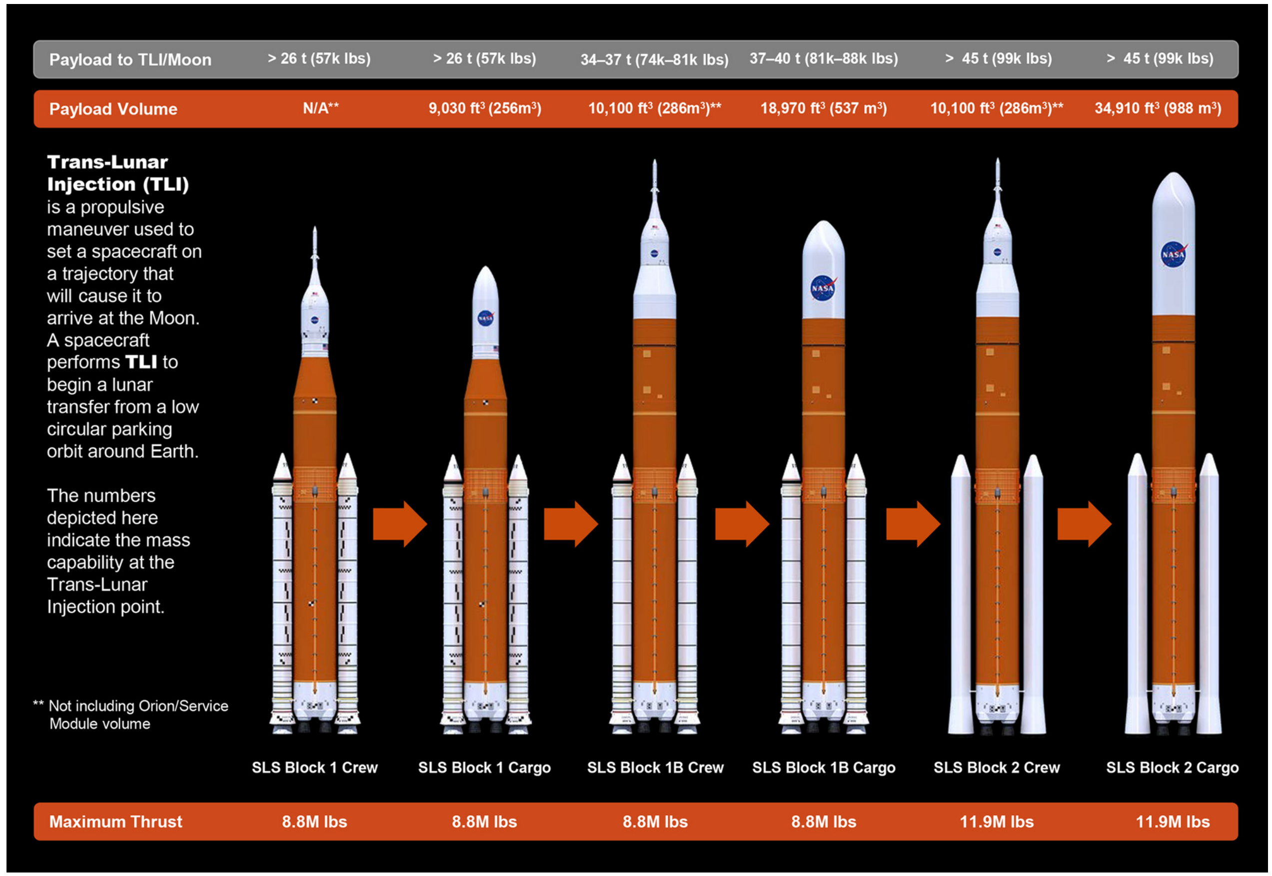
Volume rendering of mass fractions. Liquid water is colored blue. Plumes are colored yellow to purple and water vapor is white. SRBs starting indicate time T=0



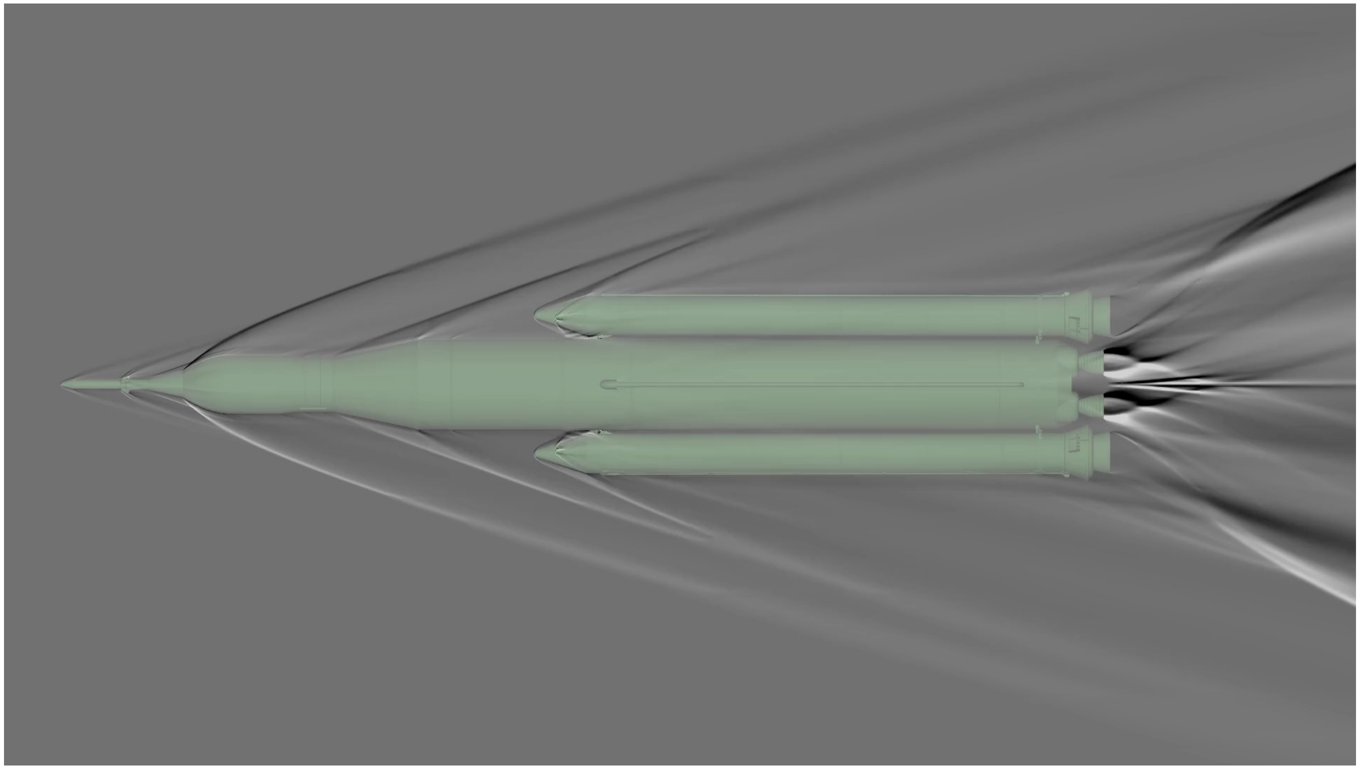


Aerodynamic Databases

1. SLS Block 1 Crew
   - ~4000 ascent cases
   - ~40k booster separation cases (two analysis cycles)
2. SLS Block 1 Cargo (discontinued)
   - ~1000 ascent cases
3. SLS Block 1B Crew
   - ~1000 ascent cases
   - ~2500 booster sep cases
   - Next up: 10k more bsep
4. SLS Block 1B Cargo
   1. ~2000 ascent (2 payload fairings)
5. SLS Block 2 Crew
   - Next up: booster sep
   - Ascent coming soon
6. SLS Block 2 Cargo
   - No foreseeable tasking



Space Launch Systems (SLS) – Stage Separation



SLS stage separation simulations showing numerical Schlieren


National Aeronautics and Space Administration

ORION

Launch Abort System (LAS)

NASAfacts

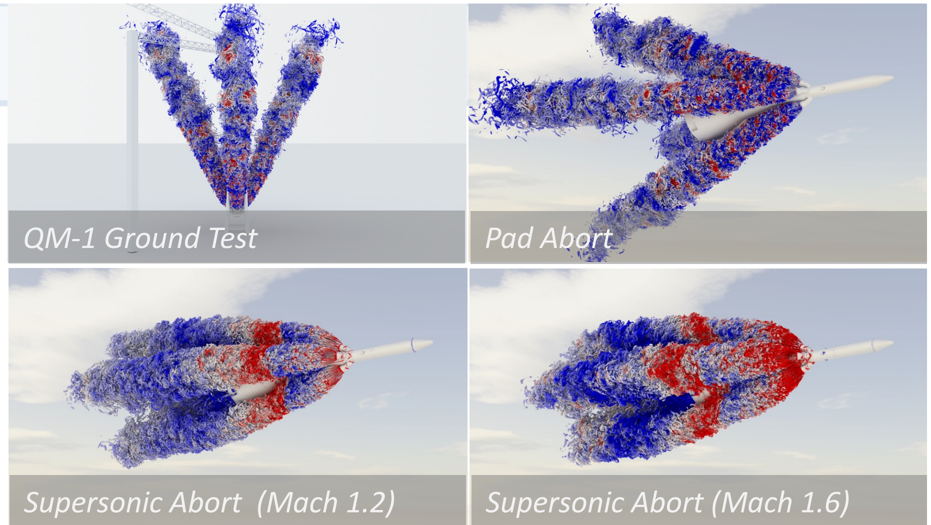
Ensuring Astronaut Safety

NASA is developing technologies that will enable humans to explore new destinations in the solar system. America will use the Orion spacecraft, launched atop the Space Launch System rocket, to send a new generation of astronauts beyond low-Earth orbit to places like an asteroid and eventually Mars. In order to keep astronauts safe in such difficult, yet exciting missions, NASA and Lockheed Martin collaborated to design and build the Launch Abort System.

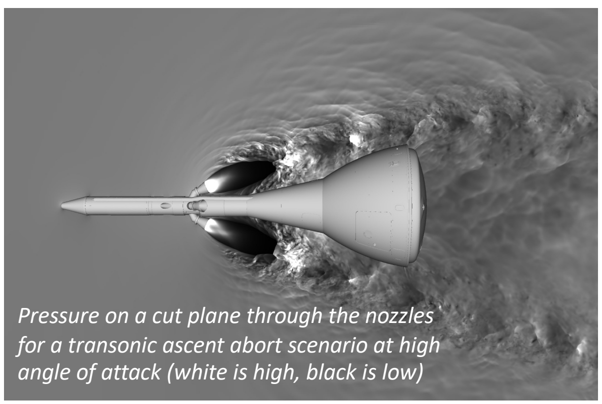
9

Predicting Orion LAS Acoustics: Wind Tunnel

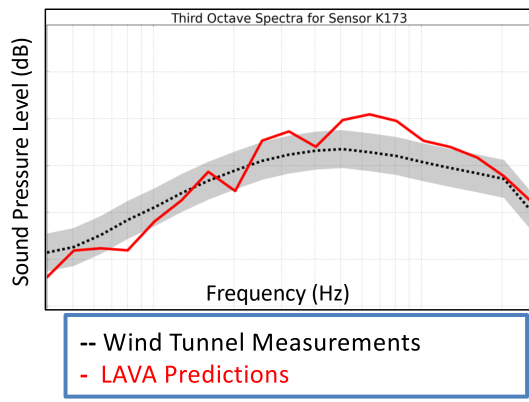
- ✓ Can CFD provide difference in vibration strength due to vehicle geometry difference with QM-1 test article? Yes, provided spatially varying expected delta-dB.
- ✓ Can CFD predict relationship between vibration strength and trajectory point obtained from wind tunnel test: altitude, velocity, angle of attack? Yes, validated predictions with wind tunnel data.
- ✓ Can CFD help reduce uncertainty in margins at high angle of attack? Yes

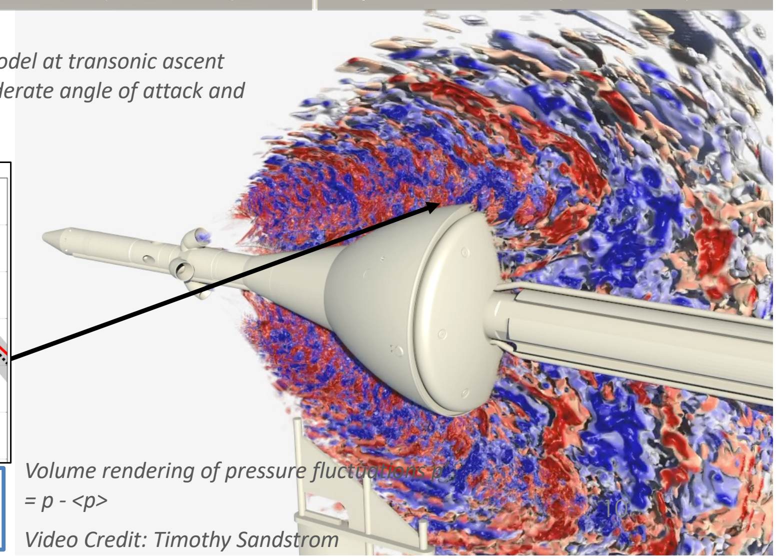


Wind tunnel model at transonic ascent abort with moderate angle of attack and side slip



Pressure on a cut plane through the nozzles for a transonic ascent abort scenario at high angle of attack (white is high, black is low)





Volume rendering of pressure fluctuations p' = p - <p>

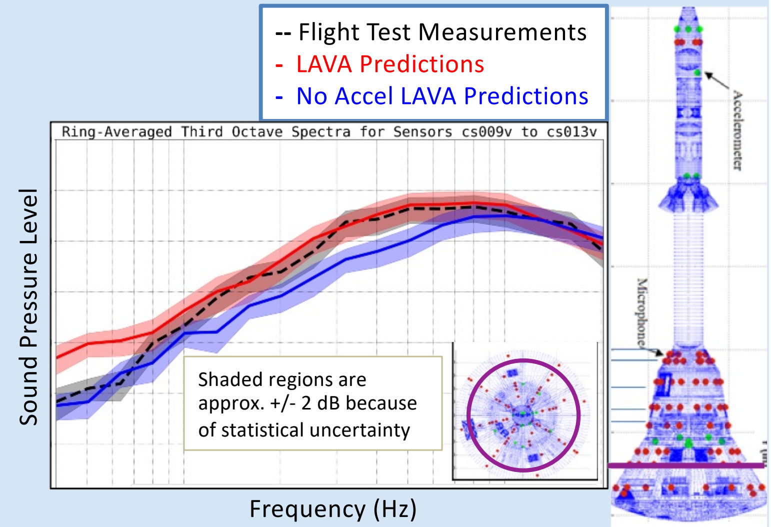
Video Credit: Timothy Sandstrom

Flight Test Validation

Pad Abort 1 flight test where Orion LAS accelerates from rest to 10x Earth's gravity

Video shows passive particles seeded at the nozzle colored by velocity magnitude: white is fast, dark orange is slow

✓ Can CFD identify difference in vibration strength due to vehicle acceleration and change in attitude? Yes, provided spatially varying expected delta-dB.



Video Credit: Timothy Sandstrom

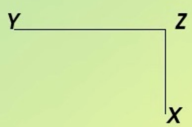
Time = +49.7336 s

Flight Test Validation

Ascent Abort 2 flight test where Orion LAS triggered at Mach 1.2

- ✓ Can CFD explain higher than expected vibration-levels recorded during AA-2 test? Yes, demonstrated that CFD predicts that vibrations do not reduce in strength as much as expected from empirical scaling laws.
- ✓ LAVA team has made a big impact on the vehicle requirements for safety:
- ✓ Prior to 2017, CFD predictions of acoustics were not used or trusted
- ✓ Now they help inform engineering decisions to ensure future astronaut's safety

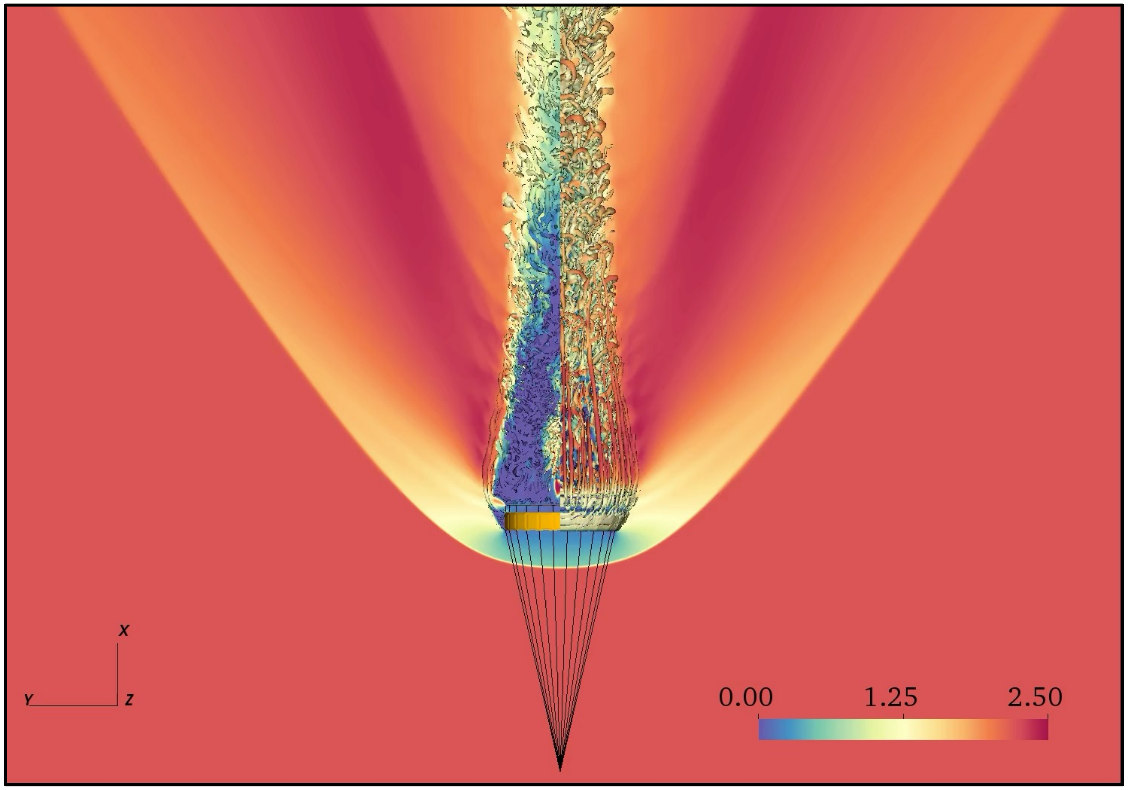
Video shows density on cut plane (red is low, blue is high), and axial velocity on the surface (black is low, white is high)



Supersonic Retro Propulsion (Mach 2.4)

Volume rendering of exhaust mass fraction where yellow is 100% and black is 1%. Only the plumes on the left side of vehicle are rendered to elucidate the plume structure without obstruction

Supersonic Parachute/Fluid-Structure Interaction

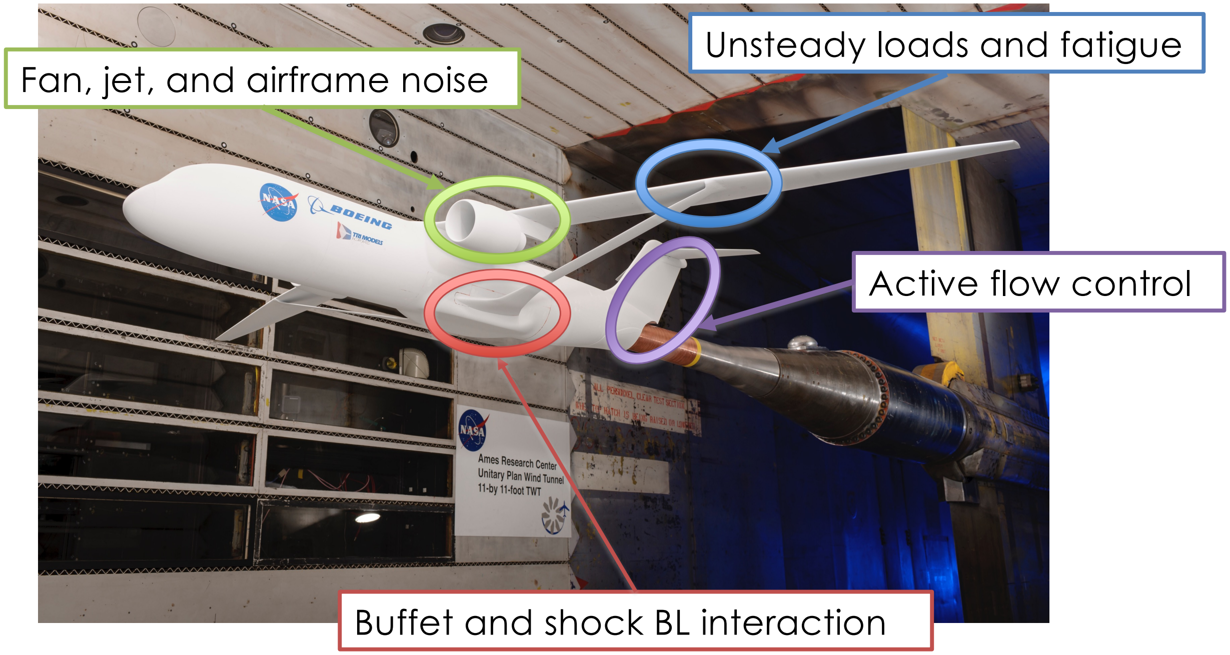


Pseudocolor contours of Mach number shown on a cut plane through the center of the domain for the impermeable parachute in M = 2.2 flow and iso-contours of Q-criterion colored by Mach number

Sustained Atmospheric Flight

✓ **Increase predictive use of computational aerosciences capabilities for next generation aviation and space vehicle concepts.**

- The next frontier is to use wall modeled and/or wall resolved large-eddy simulation (LES) to predict:



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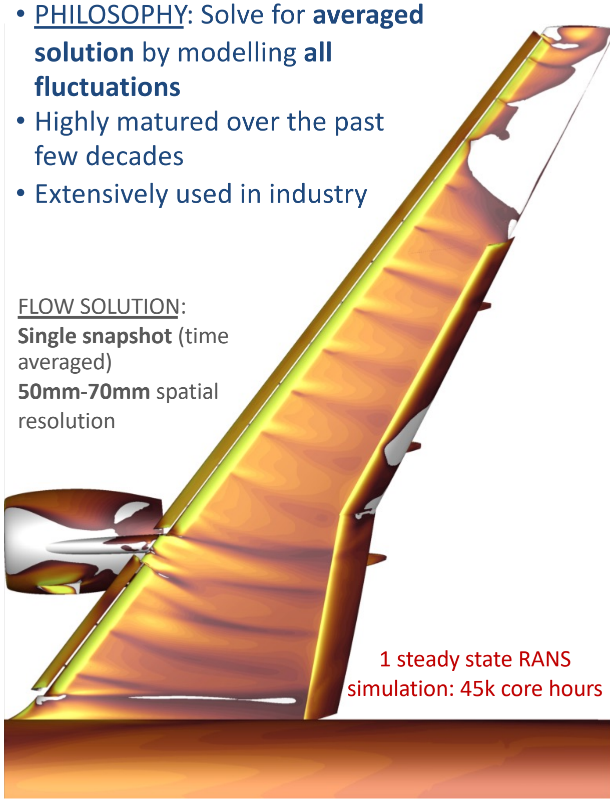
Scale resolving simulations for Certification and Qualification by Analysis

REYNOLDS AVERAGED NAVIER STOKES (RANS)

1980s - Present

- PHILOSOPHY: Solve for **averaged solution** by modelling **all fluctuations**
- Highly matured over the past few decades
- Extensively used in industry

FLOW SOLUTION:
Single snapshot (time averaged)
50mm-70mm spatial resolution

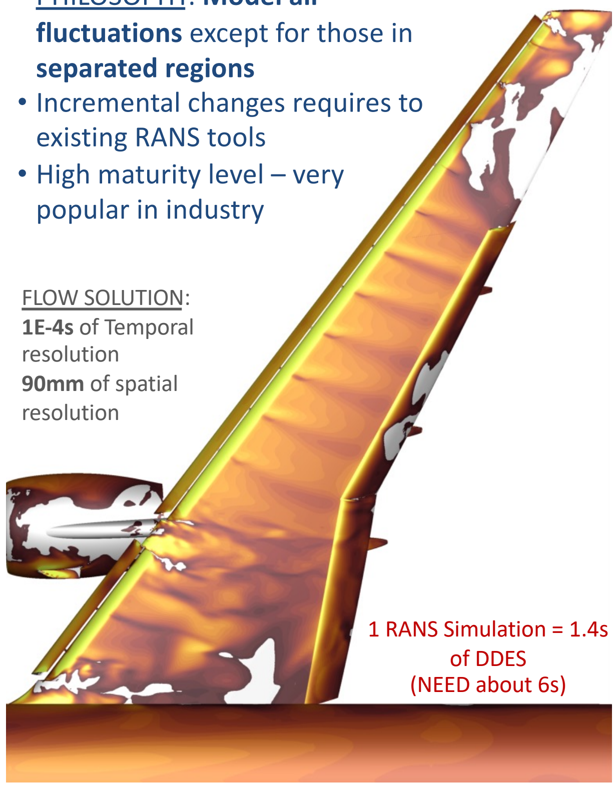


DELAYED DETACHED EDDY SIMULATIONS (DDES)

1990s - Present

- PHILOSOPHY: **Model all fluctuations** except for those in **separated regions**
- Incremental changes requires to existing RANS tools
- High maturity level – very popular in industry

FLOW SOLUTION:
1E-4s of Temporal resolution
90mm of spatial resolution

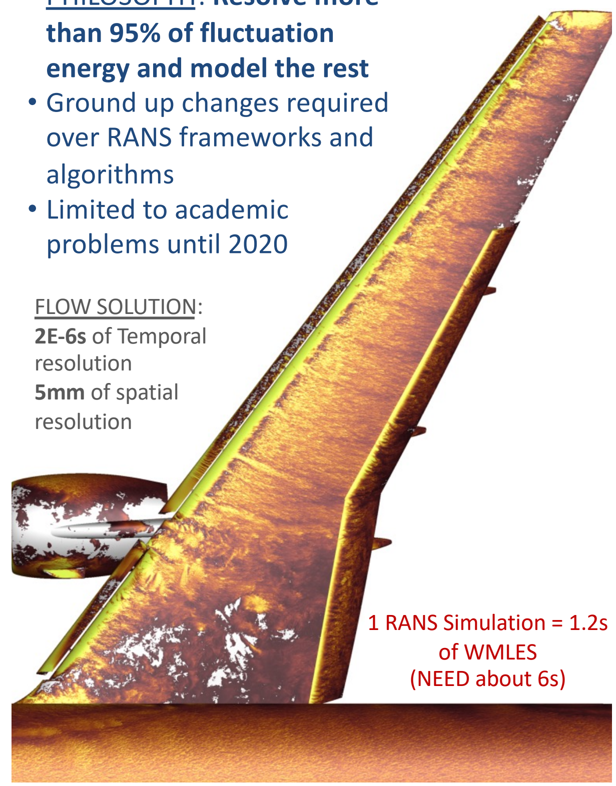


LARGE EDDY SIMULATIONS (WMLES)

2020 - Present

- PHILOSOPHY: **Resolve more than 95% of fluctuation energy and model the rest**
- Ground up changes required over RANS frameworks and algorithms
- Limited to academic problems until 2020

FLOW SOLUTION:
2E-6s of Temporal resolution
5mm of spatial resolution



C_{Lmax} Predictions using RANS, HRLES, and WMLES

PROBLEM:
- High-Lift aerodynamics on non-academic 3D geometries pose significant challenges to CFD algorithms. The HL-CRM is studied for quantifying accuracies of various turbulence treatment algorithms.

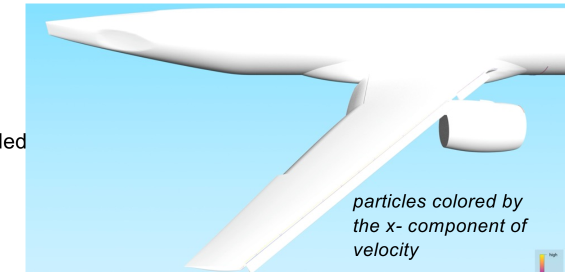
OBJECTIVE:
- Compare solution accuracies between a) RANS (Steady and Unsteady), b) Hybrid RANS/LES (HRLES), and c) Wall Modelled LES (WMLES) for the HL-CRM model.

APPROACH:
- Curvilinear structured overset grids are utilized within the LAVA computational framework. SA-model with its variants were utilized for RANS, the ZDES-EP2020 approach was used for HRLES and a constant coefficient Vreman model with an equilibrium wall-model was utilized in WMLES.

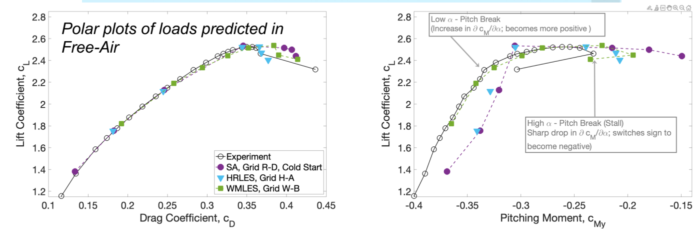
RESULTS:
- Steady state RANS showed excess separation on the outboard portions of the wing at high angles of attack. This error worsens with both grid-refinement and utilizing correction terms (such as RC and QCR). Unsteady RANS simulations did not alleviate this deficiency.
- HRLES shows stark improvement over RANS but only when LES-appropriate grids and non-dissipative discretization was used. HRLES on RANS grids produced worse results compared to RANS.
- WMLES on three-separate levels of grids ranging from 300M to 1.1B grid points produced largely consistent results. The coarsest grid utilizing aggressive off-body coarsening showed an onset of wing-root separation at a lower angle compared to the finer grids – suggesting the importance of grid resolution in capturing off-body vorticity.

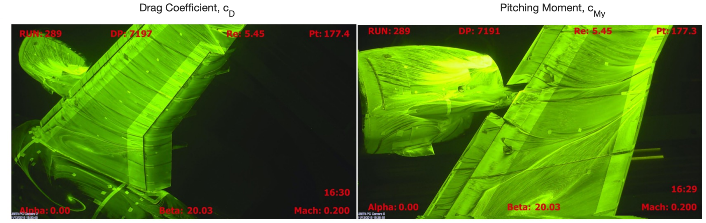
SIGNIFICANCE:
- First comprehensive comparative assessment between RANS and scale resolving methods clearly demonstrates the potential of scale resolving techniques to address the deficiencies of RANS closures for C_{Lmax} and stall prediction problems.
- The effect of time-step size (implicit time-stepping scheme) used in HR-LES clearly show the need for sufficiently resolving the small-timescales; large sensitivity is reported in wing-root separation predicted at the highest angle of attack.
- Computational cost comparisons suggest very favorable prospects for WMLES utilizing explicit time-stepping schemes that show about 5-10 times more cost compared to best-practice steady state RANS simulations.
- Major bottleneck for all the simulations was the overset grid generation; majority of grids took over several months of human effort to generate. A parallel effort utilizing WMLES with immersed boundary treatment on automatically generated octree grids has shown some promise and is currently under active development.

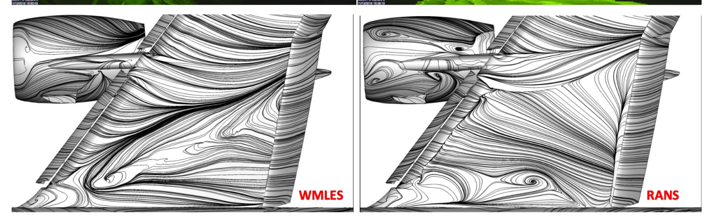
Kiris, C. C., Ghate, A. S., Duensing, J. C., Browne, O. M., Housman, J. A., Stich, G. D., Kenway, G., Fernades, L. S., Machado, L. M., "High-Lift Common Research Model: RANS, HRLES, and WMLES perspectives for CLmax prediction using LAVA," AIAA-2022-1554, January 2022, doi.org/10.2514/6.2022-1554



LAVA WMLES, Free Air, AoA: 21.47°





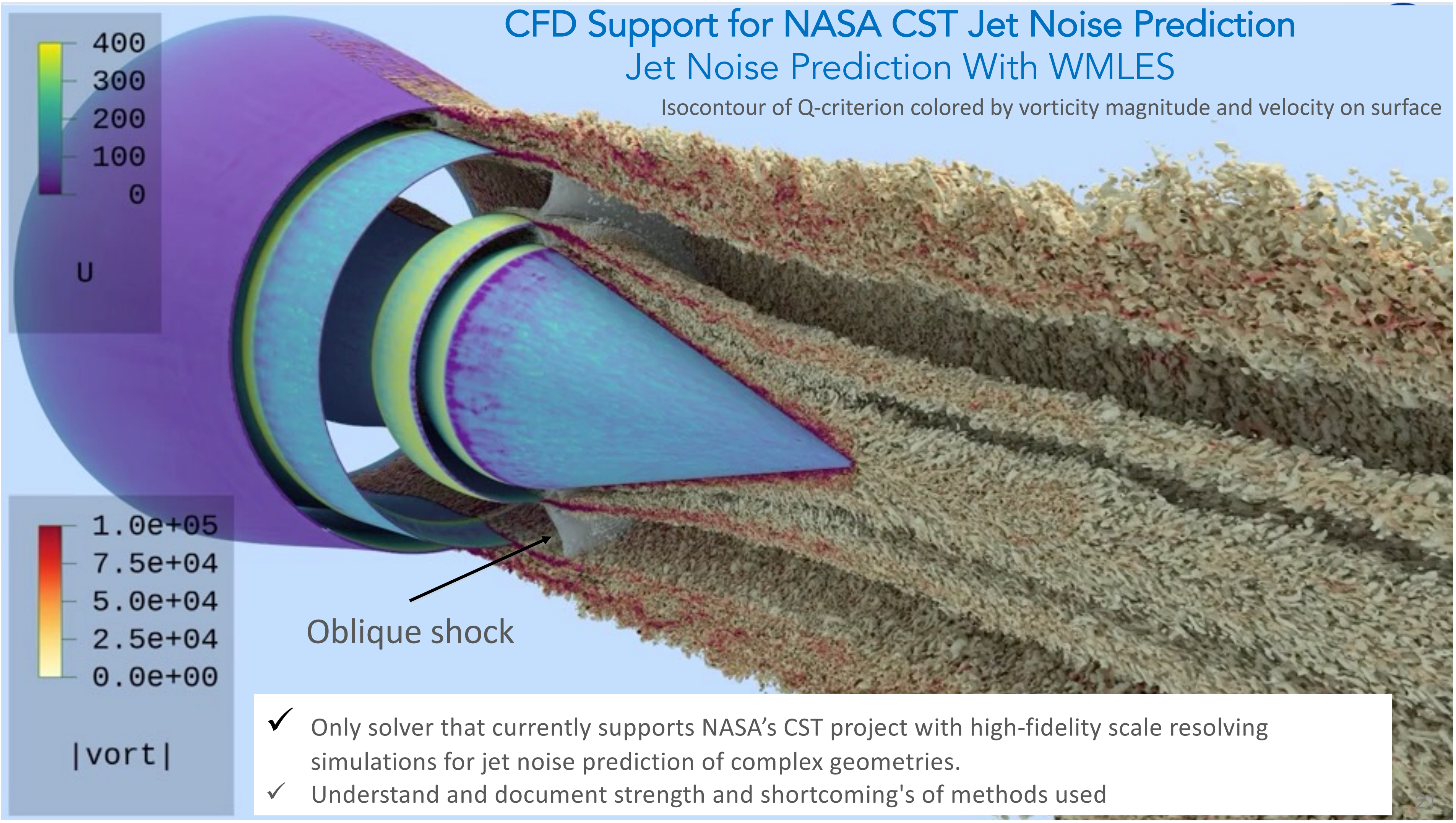


Surface streamlines for in-tunnel simulations at 19.9deg. angle of attack

CFD Support for NASA CST Jet Noise Prediction

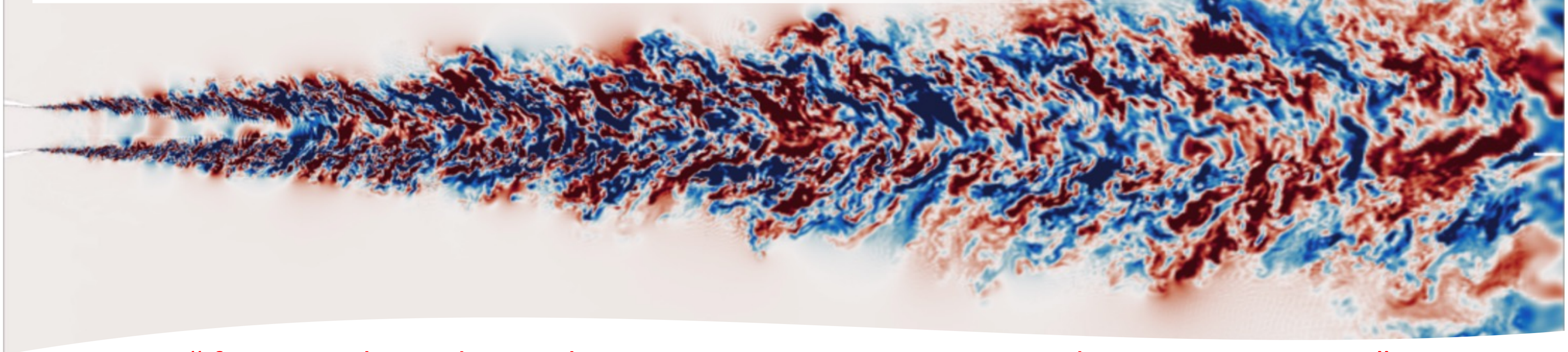
Jet Noise Prediction With WMLES

Isocontour of Q-criterion colored by vorticity magnitude and velocity on surface



- ✓ Only solver that currently supports NASA's CST project with high-fidelity scale resolving simulations for jet noise prediction of complex geometries.
- ✓ Understand and document strength and shortcoming's of methods used

Pushing the limits of scalability with modern computer architectures



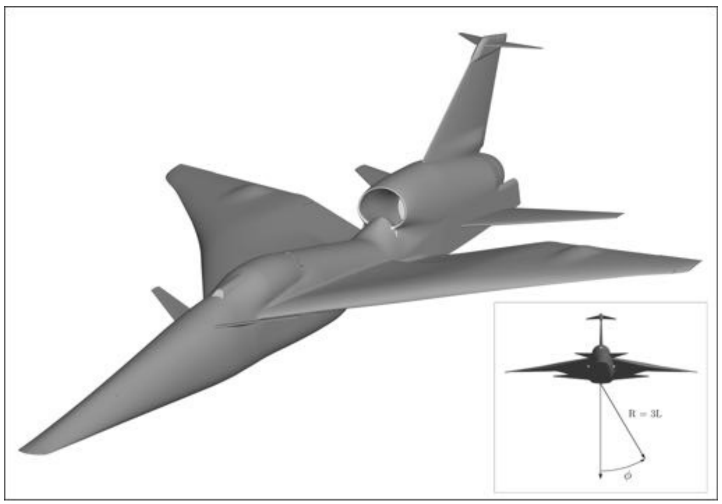
" from weeks to days to hours to minutes – 6300% speedup since Nov 2019"

Hybrid RANS/LES		Wall-Modeled LES		Wall-Modeled LES		Wall-Modeled LES
NOVEMBER 2019	2.8x	March 2020	18x	March 2020	63x	TODAY
6.5 days		2.3 days		8.6 hours		150 minutes
2400 cores Skylake		2400 cores Skylake		2400 cores Skylake		12800 cores ROME

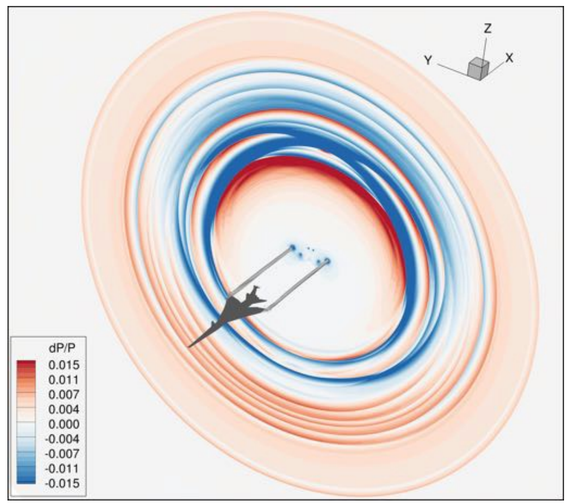
*Improvements compared to baseline November 2019

X-59 Low Boom Flight Demonstrator Analysis

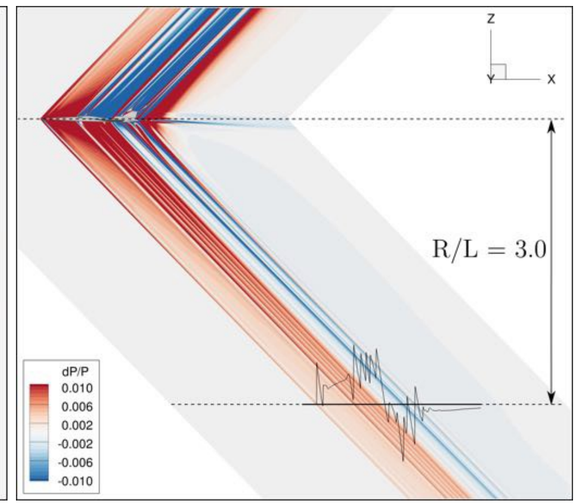
- ✓ LAVA Curvilinear is used to simulate numerous flight conditions and aircraft configurations for the X-59 Quiet Supersonic Aircraft program, generating databases of aerodynamic and noise predictions
- ✓ Refactorization of the LAVA Curvilinear flow solver has enabled near-field and far-field ground noise predictions to be generated with up to a 10X computational cost reduction
- ✓ A recently development space-marching routine coupled with the CFD solver has reduced the required CFD computational domain size, leading to simulation cost reduction



X-59 Low-Boom Flight Demonstrator aircraft



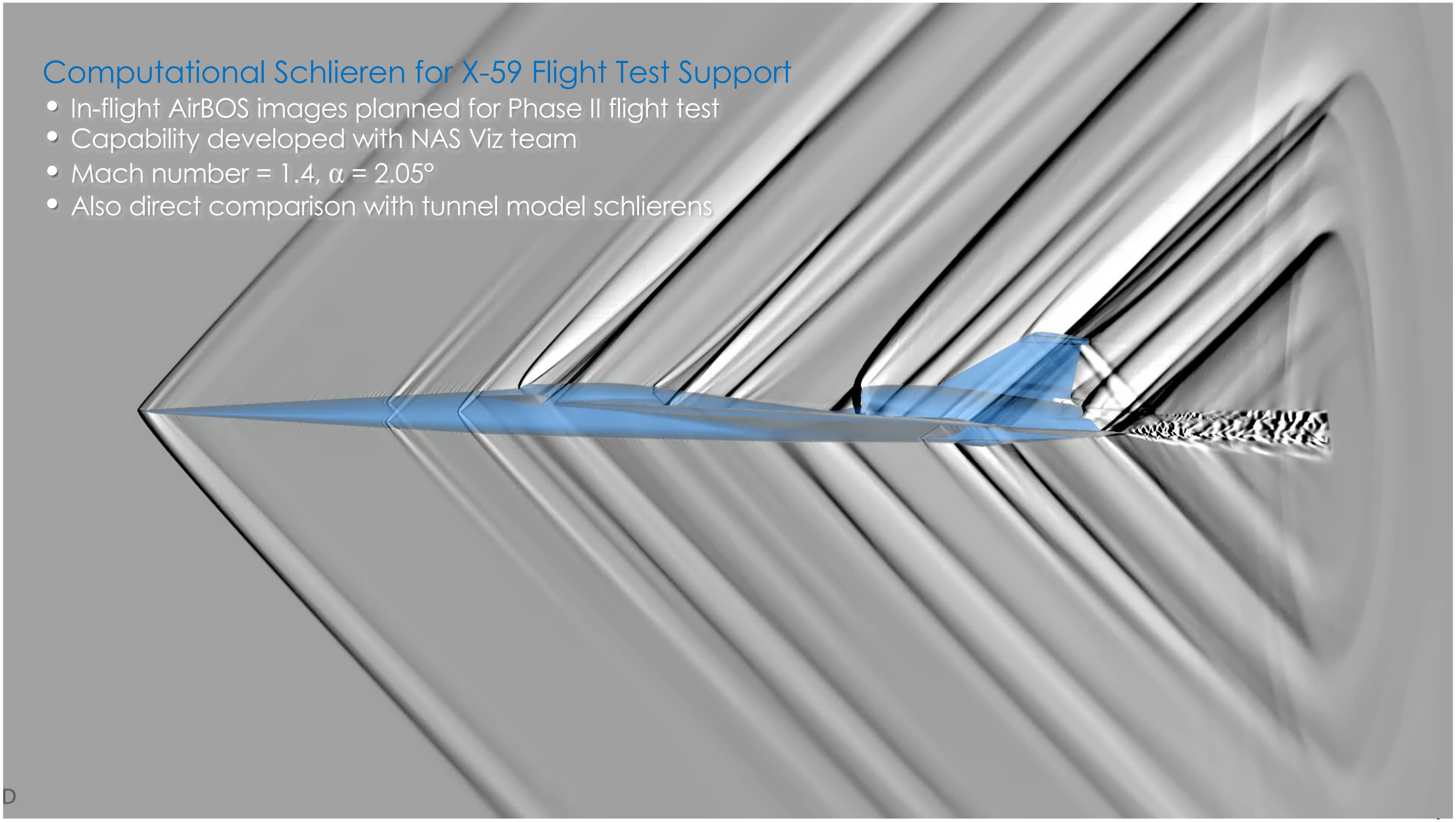
Pressure disturbance contours shown, with wingtip vortices depicted in gray



Pressure disturbance contours on symmetry plane with sample nearfield boom signature

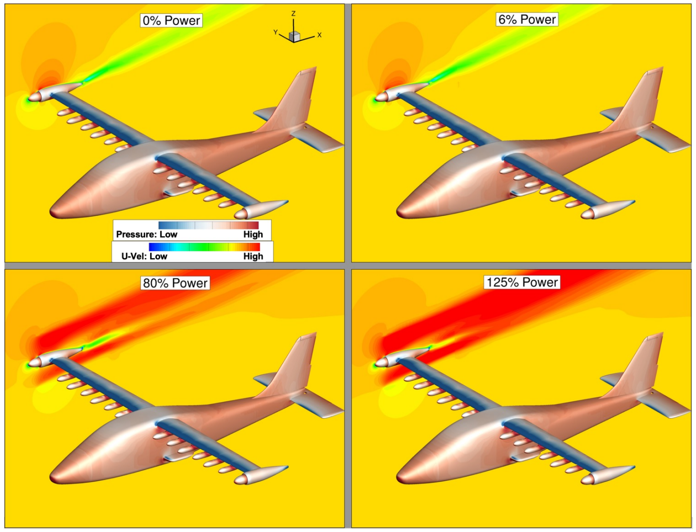
Computational Schlieren for X-59 Flight Test Support

- In-flight AirBOS images planned for Phase II flight test
- Capability developed with NAS Viz team
- Mach number = 1.4, α = 2.05°
- Also direct comparison with tunnel model schlierens

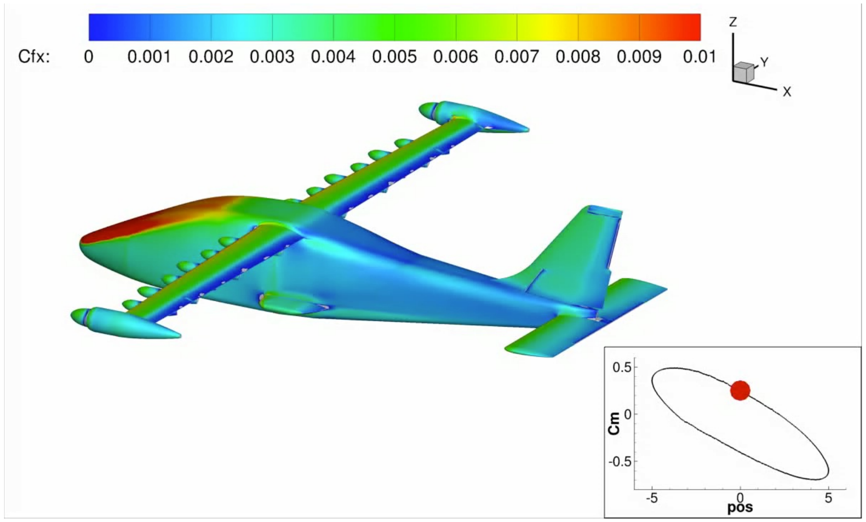


X-57 Maxwell Aerodynamic Database Generation

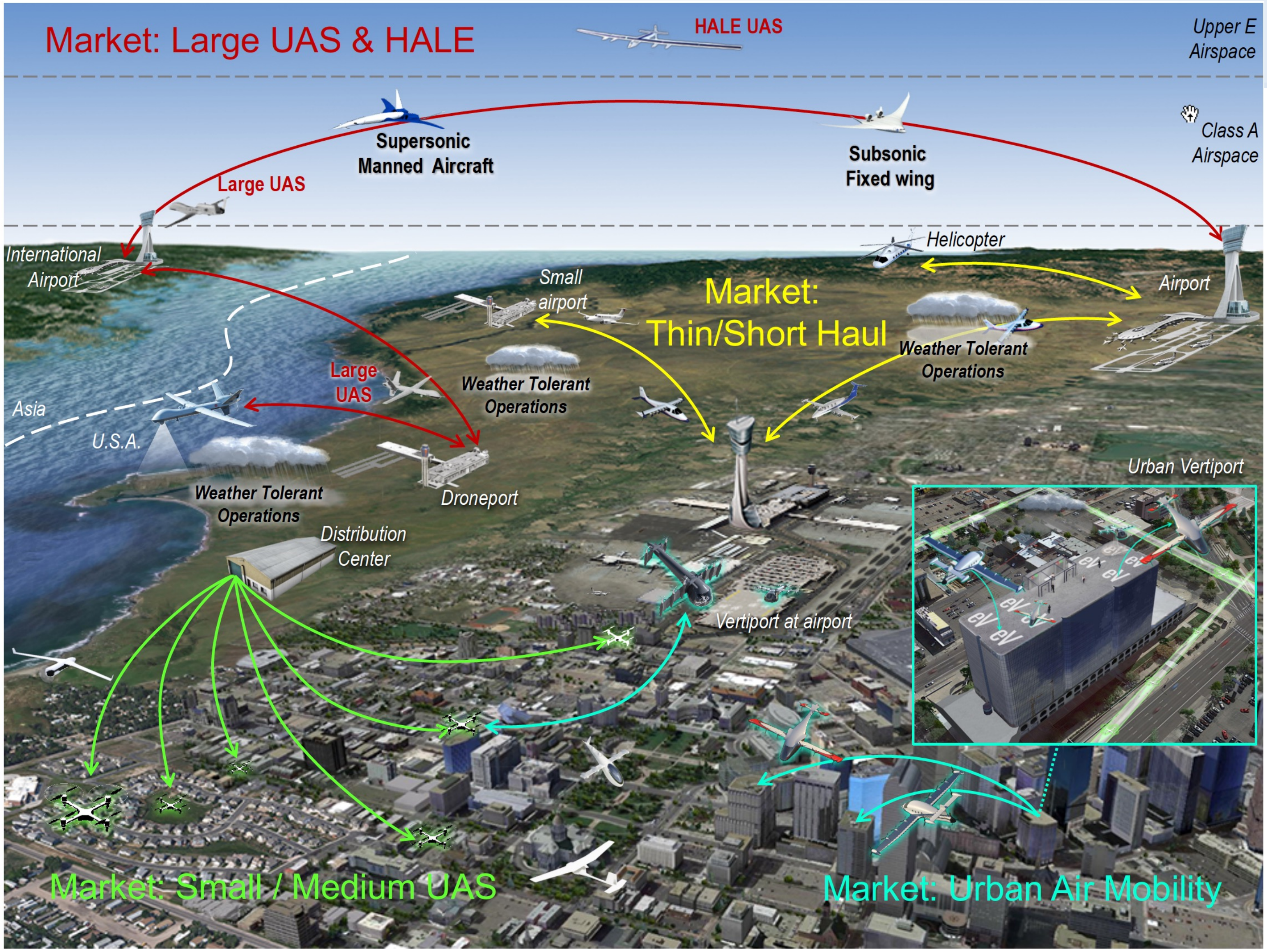
- ✓ The LAVA Curvilinear CFD flow solver has enabled the efficient generation of large-scale aerodynamic databases, quantifying the distributed propulsion effects on NASA's all-electric X-57 aircraft
  - Over 2800 steady simulations for powered and unpowered flight conditions (left image)
  - Over 40 time-accurate forced oscillation simulations to quantify dynamic stability characteristics (right image)
- ✓ Results are essential to accurately construct the piloted flight simulator, necessary to train X-57 pilots for safe flight
- ✓ Refactorization of the LAVA Curvilinear flow solver has resulted in a 9-12X reduction in simulation cost
  - Large-scale database completion time has been reduced from years to months



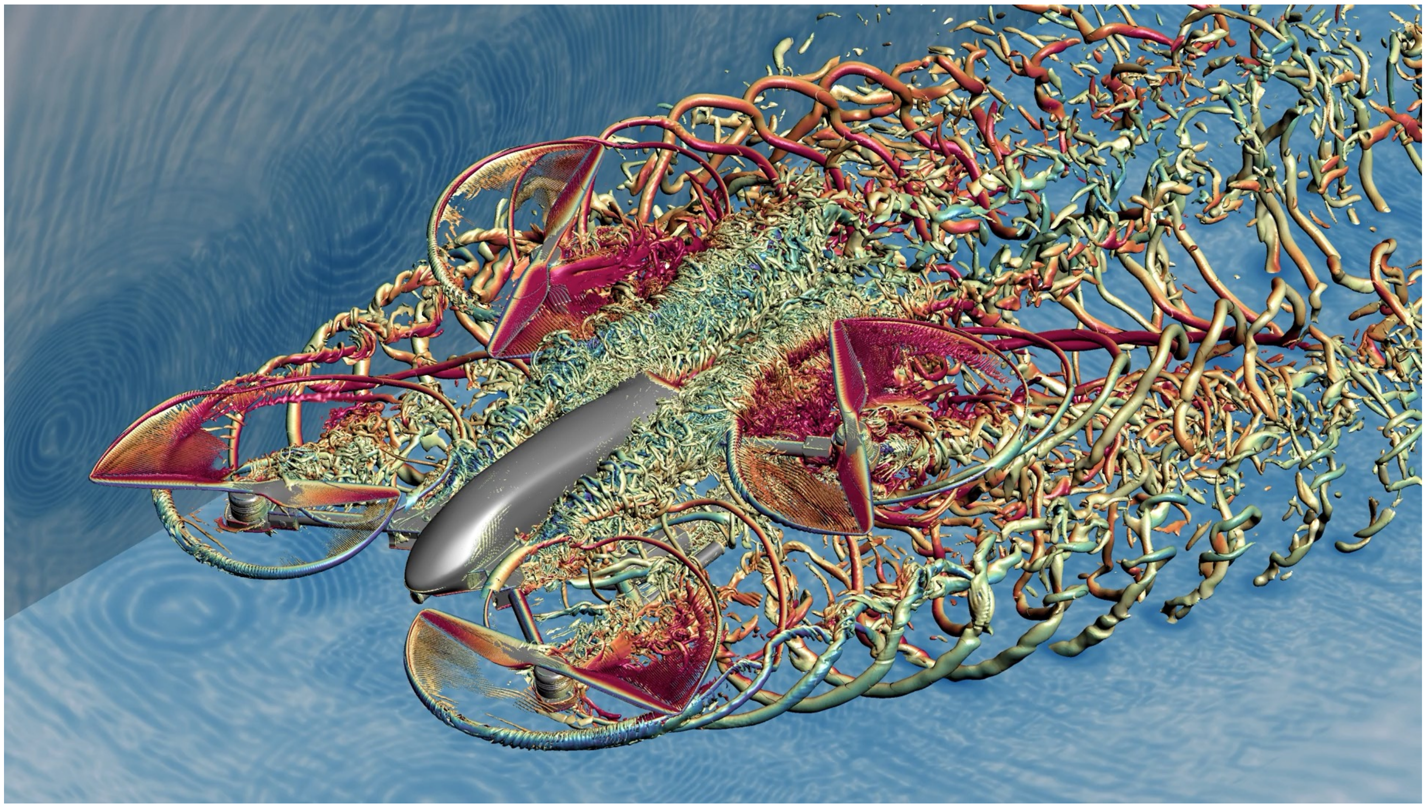
Surface pressure and streamwise velocity shown on planar slice for various database cruise power conditions.



Skin friction and pitching moment as a function of pitch angle for an unsteady forced pitch oscillation simulation.


Market: Large UAS & HALE
HALE UAS
Upper E Airspace
Supersonic Manned Aircraft
Subsonic Fixed wing
Class A Airspace
Large UAS
International Airport
Helicopter
Airport
Small airport
Market: Thin/Short Haul
Weather Tolerant Operations
Large UAS
Weather Tolerant Operations
Asia
U.S.A.
Droneport
Weather Tolerant Operations
Urban Vertiport
Distribution Center
Vertiport at airport
Market: Small / Medium UAS
Market: Urban Air Mobility

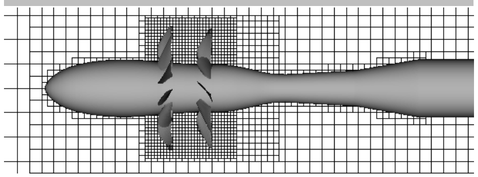
Urban Air Mobility – Noise Prediction

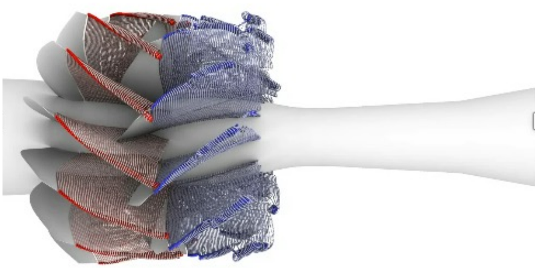


Isosurfaces of Q-criterion colored by vertical velocity and cut plane colored by logarithm of pressure gradient magnitude

Grid Paradigms in CFD

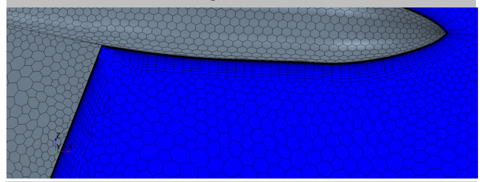
Structured Cartesian AMR

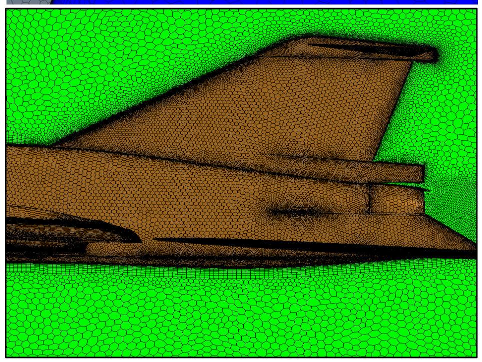




- ✓ Fully-automated grid generation
- ✓ Highly efficient Adaptive Mesh Refinement (AMR)
- ✓ Low computational cost
- ✓ Reliable higher order methods
- ✗ Non-body fitted → Resolution of boundary layers challenging

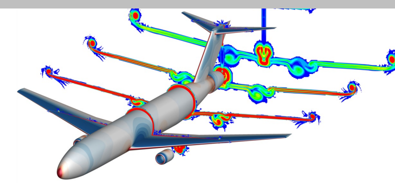
Unstructured Arbitrary Polyhedral

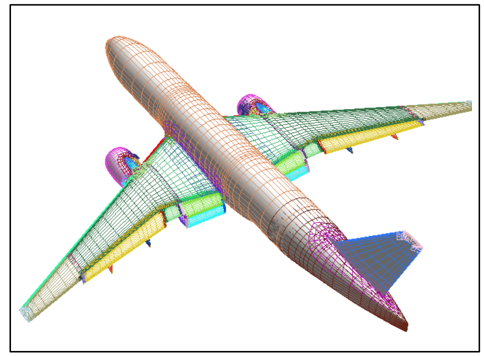




- ✓ Partially automated grid generation
- ✓ Body fitted grids
- ✗ Grid quality can be challenging
- ✗ High computational cost
- ✗ Higher order methods yet to fully mature

Structured Curvilinear





- ✓ High quality body fitted grids
- ✓ Low computational cost
- ✓ Reliable higher order methods
- ✗ Grid generation largely manual and time consuming

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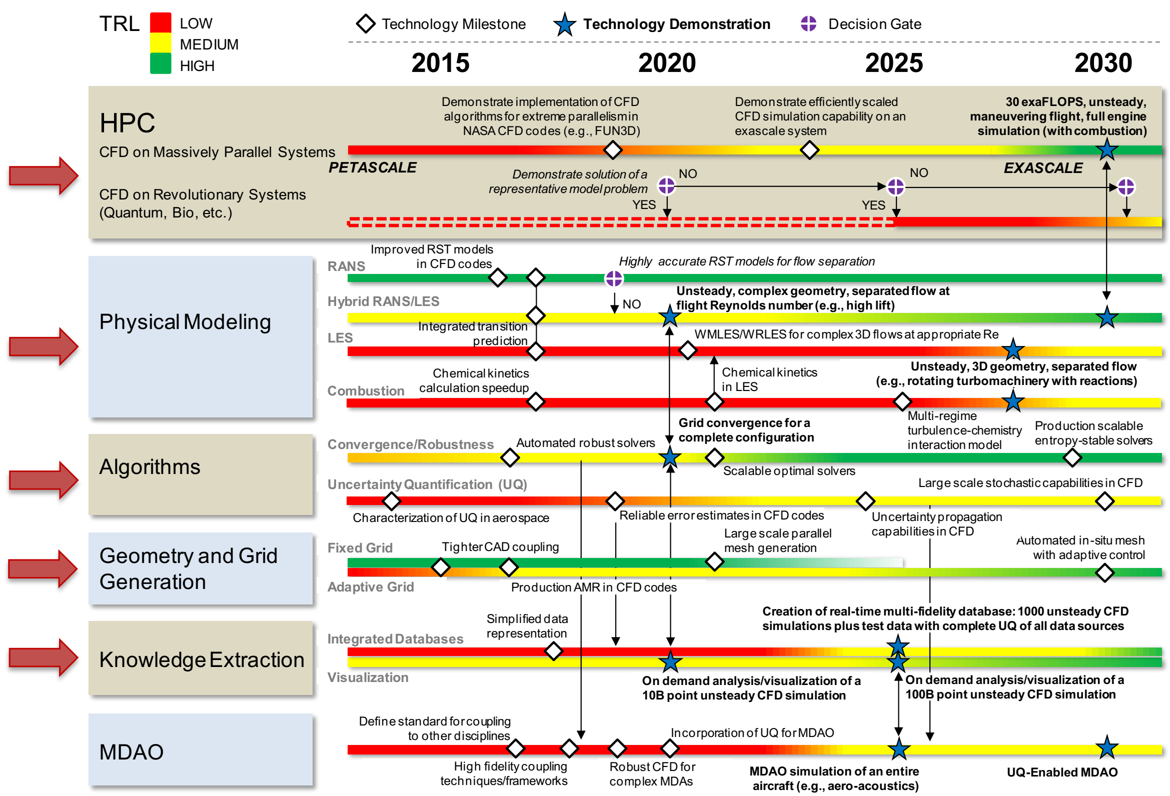
CFD 2030 Technology Development Roadmap



CFD Vision 2030 Study report published in 2014